行政院國家科學委員會專題研究計畫成果報告

高速推進器設計與性能解析研究(II)- 穿水式翼面性能解析
An Analysis of Flow Around Ventilated Hydrofoils

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主持人：黃維信　　國立台灣大學造船及海洋工程學系

一、中文摘要

本計畫探討翼面高速運動時，受自由液面影響所導致之性能變化。由於翼面在自由液面附近高速運動時，可能產生兩種情形，一種是空蝕，另一種情形是空氣被吸入翼面的低壓區。本年度計畫，我們考慮當空蝕泡出現時，受到自由液面影響，空蝕泡將會如何變化，並討論二維翼其空蝕泡與空蝕係數間的關連。使用邊界元素法為工具，以非線性模式取代線性模式，解析部分或全空蝕二維翼面性能，空蝕泡與空蝕係數之間的關係，空蝕泡與翼面前緣厚度與幾何形狀間的關係，升力係數受翼面拱高與厚度變化所產生的影響，吃水變化對空蝕泡及升力係數造成的影響。

關鍵詞：空蝕泡、水翼

Abstract

The present proposal considers the free-surface effect on the high-speed hydrofoils. Both cavitation and surface ventilation may occur in the near fields of high-speed hydrofoils. First, we shall study the fully and partially cavitating bubbles when the bubbles are near the free surface and discuss the change of hydrofoil lift due to cavitating bubbles and free surface. The lifting force on such a composite model is calculated under the free-surface assumption. All the computations are based on nonlinear equations instead of the conventional linear equations.

Keywords: Cavitation, Hydrofoils

二、緣由與目的

Cavitating flows in two-dimensions have been addressed for a long time by using the hodograph technique in details see Birkhoff & Zarantonello (1957). However, due to the difficulty of extending this technique to three-dimensions, the linear theory was, somehow, preferred to analyze cavitating flows even for two-dimensional hydrofoils. The linear theory applies the results developed in the thin foil theory and assumes the ratio of the cavity and the chord lengths is also small. Many references of such applications based on the linear theory could be found in Tulin & Hsu (1980). Although the linear theory is very successful in the analysis of fully wetted foils, a serious defect arises when cavitation bubbles occur on the suction sides of hydrofoils. Uhlman (1987) first developed a nonlinear numerical method to investigate the effects of hydrofoil thickness and camber on cavity volume. After that, the nonlinear boundary integral method has become the main tool to solve the flow problems due to a partial or super cavitation. Different formulations based on the boundary integral equations [6] - [11] were derived by many researchers in the last few years. Except boundary integral methods, Kinnas (1991) also presented a nonlinear leading-edge correction formula to account for the breakdown in the linear theory.

The modeling of cavitation flows around hydrofoils has great progress recently, and most of them are concentrated on the deeply submerged hydrofoils. However, for marine propellers or hydrofoils the free surface effect is not negligible. In fact, not much attention was put on the free surface effect for the cavitating flows. Only few reports were presented in the literature such as Furuya (1975), in which numerical procedures of hodogragh technique were applied to solve a two-dimensional supercavitating flows near a free surface. No modeling of cavitating flows near a free surface is discussed by using the boundary integral method. In this paper a boundary integral model is proposed to study the partial cavitating flows around hydrofoils near a free surface.

三、結果與討論

Consider the steady, irrotational flow of an inviscid, incompressible liquid past a two-dimensional cavitating hydrofoil near a free surface. A sketch of hydrofoil is shown in Fig. 1. The cavity detaches from the foil surface at point D and reattaches the foil at point R on the suction side of the foil. The flow in the liquid is a potential flow and has a potential function, c, which satisfies the Laplace equation

$$\nabla^2 c = 0$$

A disturbance potential, ¤, can be defined by

$$c = Ux + ¤$$

where U is the freestream velocity in the x direction and the disturbance potential ϕ also satisfies the Laplace equation in the liquid domain. In addition, the following boundary conditions on c are needed.

(1) The linearized free surface boundary condition applied at the undisturbed free surface:

$$c_{xx} + ¬ c_y = 0,$$

$$¬ = g / U^2 \quad \text{at } y = 0.$$

(2) Kinematic boundary condition: the flow is tangent to the wetted hydrofoil and to the cavity surface. Then the kinematic boundary condition is given by

$$\frac{\partial \Phi}{\partial n} = 0$$

where n is the normal direction of the wetted foil and cavity surface.

(3) Dynamic boundary condition on the cavity surface: the pressure is required to be equal to the vapor pressure on the cavity surface from D to T.

$$p = p_v,$$

where p_v is the vapor pressure inside the cavity. Applying Bernoulli's equation and the definition of the cavitation number,

$$\sigma = \frac{p_\infty - p_v}{\rho U^2 / 2}$$

(4) Kutta condition:

$\nabla\Phi$ = finite, at the trailing edge of the foil.

(5) Condition at infinity:

$\nabla c \rightarrow U\mathbf{i}$, when $x \rightarrow -\infty$,

$\nabla\Phi$ = finite, when $x \rightarrow \infty$.

(6) Cavity termination model: a termination model is necessary at the cavity trailing end. It may be chosen from several existing models [4]-[6], such as the open model, the closed model, or the closed model with near wake. In the present paper, we adopt a closed termination model with a transition zone (between T and R in figure 1) proposed by Lemonnier & Rowe (1988). By applying the assumption of modeling and Bernoulli's equation, the total velocity on the cavity surface is expressed as

$$v_t = v_c [\, 1 - f(s) \,]$$

where $v_c = U(1 + \sigma)^{1/2}$ is the cavity velocity. The function f is corresponding to a prescribed law at the trailing edge of cavity.

$$f(s) = \begin{cases} 0, & s < s_T \\ A(s - s_T / s_R - s_T)^{\nu}, & s_T < s < s_R \end{cases}$$

Here, s is the arclength of the foil beneath the cavity measured from the trailing edge of cavity (T), and A (0<A<1) and ν (ν >0) are constants.

Boundary Integral Method

In this section the direct integral method is used for convenience. Before applying Green's formula, the Green's function satisfying a free surface condition is needed. The velocity potential of a submerged source located at (a, b) satisfying the Laplace equation and linearized free surface boundary condition can be found in Wehausen and Laitone.

$$G=\frac{ln\,r}{2®}+\frac{ln\,r'}{2®}+3e^{¬(y+b)}\,sin¬(x-a)$$
$$-\frac{1}{®}PV\int_0^{\infty}\frac{e^{k(y+b)}\cos k(x-a)}{k-¬}dk \qquad (2)$$

where $r=\sqrt{(x-a)^2+(y-b)^2}$ and $r'=\sqrt{(x-a)^2+(y+b)^2}$. The Green's formula for a total velocity potential in the exterior of a smooth body was given in Hwang and Huang [13]. In this paper, a modified formulation with a simple wake model is added into for hydrofoils with trailing edges.

$$(1-£)c(P)=-\int_W ac_s\frac{\hat{o}G}{\hat{o}n_Q}dS_Q+$$
$$c_I(P)-\int_S\left\{c(Q)\frac{\hat{o}G}{\hat{o}n_Q}-G\frac{\hat{o}c}{\hat{o}n_Q}\right\}dS_Q \qquad (3)$$

where Φ is the total velocity potential, Φ_I is the incident potential, W represents the wake, and $\Delta\Phi_s$ is the potential jump across the line of wake.

Usually, Eq. (3) is used to solve the unknown velocity potential at wetted boundary S and the normal velocity at the cavity surface. On the cavity surface, an expression for the velocity potential may be obtained by integrating the velocity along the cavity surface.

$$\Phi(s)=\Phi(0)+v_c\int_0^s[1-f(t)]dt \qquad (4)$$

where t is the length along the cavity surface, and Φ(0) is the velocity potential at the detachment which is extrapolated in terms of the unknown potentials in front of the cavity. The cavity surface S_c is unknown and needed to be determined by iteration during the calculation. The second integral in the left-hand side of Eq. (3) means the mass flux through the surface S_c. Although the shape of the surface S_c may vary, this integral remains unchangeable, and it is combined into the first integral during computation. The height of cavity, h(s), can be corrected by the following relationship which is valid up the first order [7]:

$$v_c[1-f(s)]\frac{dh}{ds}=\frac{\partial\Phi}{\partial n} \qquad (4)$$

In the above relation, since the trailing edge of the cavity has to stay on the surface of the hydrofoil, the height of the end point, $h(s_R)$, must be zero. For this chosen model, this termination condition is required to make sure the cavity is reattached to the surface of the hydrofoil, and to determine the cavity velocity during the computation. This condition can be expressed as

$$\int_0^{S_R}\left(\frac{\partial\Phi}{\partial n}\right)/[1-f(s)]ds=0$$

In this paper, only constant source and doublet panels are used to approximate the surface of hydrofoil.

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五、成果自評

本研究內容與原計畫相符、並達成大部份預期目標、研究成果兼具學術及應用價值、適合在學術期刊發表。